THERMAL PERFORMANCE OF RESIDENTIAL HOUSE USING INTERLOCKING COMPRESSED EARTH BRICK (ICEB) AS AN ALTERNATIVE WALL MATERIAL

RUZAIMAH BINTI RAZMAN

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Faculty of Civil and Environmental Engineering
Universiti Tun Hussein Onn Malaysia

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ABSTRACT

Buildings are usually designed and constructed without the concern of its impact to the environment and human comfort. Most contributes to poor thermal performance and high energy consumption. Over the years, in Malaysia, there has been an increasing interest in the use of interlocking compressed earth bricks (ICEB) - formed from stabilized earth - for masonry buildings. Due to its green characters and economical benefits, ICEB has gained wide recognition for use in the construction of building envelope systems. Since little information is available on the thermal performance characteristics of ICEB, a laboratory testing and simulation analysis was done to investigate its thermal insulation characteristics and to look at its thermal performance when applied as wall material for a residential building. Thermal properties of ICEB (k-value, R-value and U-value) were obtained by using Guarded Hot Plate Laboratory Testing. Field measurement of a sample house with fired clay brick as the wall material was undertaken over three consecutive days to confirm the existence of thermal comfort problems. Indoor environmental parameters measured include air temperature, mean radiant temperature and relative humidity; while the measured outdoor environmental parameters were air temperature and relative humidity. Thermal simulation of a sample house was done by using ECOTECT Software and results attained were compared with field measurements data for verification. For purpose of parametric study, the wall of the model was replaced with ICEB brick. This is to determine the effect of using the brick as compared to the common brick used in the real house. It has been found from the simulation that ICEB performed better thermally as compared to fired clay brick particularly during the daytime; however, due to the high thermal mass of ICEB, more heat will be released into the indoor spaces at night time. Nevertheless, the night time indoor temperature due to ICEB is still within the comfort range. It also showed that spaces with larger areas of enclosures made of materials with high k-value such as glass window and sliding door will have slightly higher indoor air temperature.

ABSTRAK

Bangunan biasanya direka dan dibina tanpa mengambilkira kesan terhadap alam sekitar dan keselesaan penghuni. Kebanyakan bangunan tersebut hanya menyumbang kepada prestasi haba yang lemah dan penggunaan tenaga yang tinggi. Kini, penggunaan batu bata kunci termampat (ICEB) yang dihasilkan daripada tanah liat banyak digunakan dalam industri pembinaan di Malaysia. Jika dilihat dari segi penjimatan kos dan ciri-ciri kelestarian, ICEB lebih praktikal untuk digunakan berbanding batu bata tanah liat. Disebabkan maklumat yang terhad berkaitan fungsi haba ICEB di Malaysia, ujikaji makmal dan simulasi komputer telah dijalankan untuk mengenalpasti ciri-ciri penebat haba dan melihat bagaimana ICEB berfungsi sebagai bahan dinding menggantikan batu bata tanah liat. Sifat terma ICEB (nilai konduksi, nilai kerintangan & nilai pemindahan haba) diperolehi dengan menjalankan ujikaji menggunakan *Guarded-Hot Plate Laboratory Testing.* Kerja lapangan di rumah sampel yang menggunakan batu-bata tanah liat sebagai bahan dinding telah dijalankan selama tiga hari berturut-turut. Parameter persekitaran dalaman yang diambil adalah seperti suhu udara, suhu bahangan, kelembapan udara dan halaju udara; manakala parameter persekitaran luaran termasuk kelembapan udara dan suhu udara. Data tersebut kemudian dianalisis dengan menggunakan Perisian ECOTECT dan hasil dari simulasi tersebut telah dibandingkan dengan data dari kerja lapangan untuk memastikan perisian tersebut sesuai dan boleh digunapakai. Bagi tujuan kajian parametrik, dinding model bangunan digantikan dengan bata ICEB. Ini adalah bertujuan untuk menentukan kesan penggunaan ICEB berbanding batu bata tanah liat apabila digunakan pada rumah sebenar. Hasil perbandingan menunjukkan bahawa ICEB berfungsi lebih baik berbanding dengan batu bata tanah liat terutamanya pada waktu siang tetapi disebabkan oleh jisim haba yang tinggi, ICEB cenderung untuk membebaskan lebih banyak haba ke dalam bangunan pada waktu malam. Walau bagaimanapun, suhu tersebut masih dalam lingkungan selesa. Ia juga menunjukkan bahawa zon yang terdiri daripada bahan-bahan dengan nilai kekonduksian tinggi seperti pintu dan tingkap kaca akan lebih menyumbang kepada peningkatan suhu dalaman bangunan.

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LIST OF SYMBOL AND ABBREVIATIONS

ICEB	Interlocking Compressed Earth Bricks
CFCs	chlorofluorocarbons
CO_2	Carbon Dioxide
ASEAN	Association of Southeast Asian Nations
mcm/d	million cubic metres per day
M	metabolic activity (1 met = 58 W/m^2)
I_{cl}	clothing value (1 clo = 0.155 m^2K/W)
T_a	air temperature
Rh	relative humidity
T_{mrt}	mean radiant temperature
v	air velocity
C_v	convection
C_d	conduction
E	evaporation heat loss
ΔS	change in the heat stored
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
$T_{max,\ Icl}$	upper operative temperature limit for clothing insulation
$T_{min,\ Icl}$	lower operative temperature limit for clothing insulation
I_{cl}	thermal insulation of the clothing in equation (clo)
HVAC	heating, ventilation and air-conditioning system
k-value	thermal conductivity (W/mC)
R-value	Resistance (m^2C/W)
U-value	Transmittance (W/m^{2o}C)
Q	heat capacity (Wh/m^2K)
CSIRO	Commonwealth Scientific and Industrial Research Organization
T_o	Operative temperature

Q	rate of heat transfer (W)
A	area of heat transfer normal to the direction of heat flow (m^2)
L	thickness of the brick (m)
ΔT	temperature different between warm and cold surface (^oC)
R^2	coefficient of regression model

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CHAPTER 1

INTRODUCTION

1.1 Background

In Malaysia, most residential buildings in urban areas are composed of homogenous large scale housing. These are often built with little attention to whether its details and design can provide a comfortable living condition to its occupants. The building envelope, which is the most important parameter of the passive system affecting indoor climate, separates the indoor space from the external environment and in this way changes the amount of heat flow through itself. Thus, the design of building envelope is the basic determinant of the indoor climate and also of the demand for supplementary mechanical energy. Common are complaints from occupants where the indoor temperature raises beyond the acceptable comfort levels. This has created unbearable living conditions and can be linked to other health and psychological problems.

Recently, due to its green characters and economical benefits, Interlocking Compressed Earth Bricks (ICEB) formed from stabilized earth has gained wide recognition for use in the construction of building envelope systems. Since little information is available on the thermal performance characteristics of ICEB, a testing program and simulation analysis were developed to investigate the thermal insulation characteristics of ICEB commercially available at present. With regard to determination of appropriate building envelope and operation period, an approach aiming to provide the climatic comfort in most economical and sustainable manner was investigated in this study.

1.2 Problem statement

Building and construction activities worldwide consume 3 million tons of raw materials each year or 40 percent of total global use (D. M. Roodman & N. Lenssen, 1995). Using green building material and product promotes conservation of dwindling non-renewable resources internationally. In addition, integrating green building materials into building projects can help reduce the environmental impacts associated with the extraction, transport, processing, fabrication, installation, reuse, recycling, and disposal of these building industry source materials.

Green building materials are composed of renewable, rather than non-renewable resources. Green materials are environmentally responsible because impacts are considered over the life of the product (Ross Spiegel & Dru Meadows, 1999). In nearly all hot-dry, and moderate climates of the world, earth has been the predominant building material. Earth structures are completely recyclable, so sun-dried bricks return to the earth without polluting the soil (Rigassi, 1995). Using earth for such environmental-friendly buildings will be a strong component in the future of humankind (After Yaser Khaled A. A., 2009). In addition, energy requirement to produce for example adobe block is only 5 (kWh)/cubic meter while for fired brick is 1000 (kWh)/cubic meter and 400-500 (kWh)/cubic meter for concrete (After Yaser Khaled A. A., 2009).

During last few years, there has been a growing interest in the use of earth as a modern construction material and also considered as a sustainable material. Some of the reasons for this are the energy saving in manufacturing compared to clay bricks, the cement used was compared to concrete blocks, the transportation savings, if soil comes from the construction site or vicinity and the natural appearance and colours that help buildings integrate into the landscape (Carmen and Ignacio, 2005). Malaysia also produced this unburnt clay brick used for residential building. However the thermal characteristic and performance of this unburnt brick is not well investigated. These initiated the author to study the thermal characteristic of the brick and also its performance as wall of residential building.

1.3 Research objectives

The objectives of this study are to:

1. Determine thermal properties of ICEB.
2. Determine thermal comfort level of the selected building.
3. Simulate and verify the thermal environment of the building using ECOTECT program.
4. Parametric study by replacing the common brick with ICEB brick of the building using ECOTECT program.

1.4 Research scope

The scopes of the study are as follows:

1. Samples of ICEB used are produced from local manufacturer.
2. The selected building is an intermediate terrace house (single storey) in Batu Pahat, Johor.
3. This study focuses on using natural ventilation only.
4. This study considers no contribution from indoor heat gain.
5. The indoor thermal performance considered is only operative temperature.

1.5 Structure of the Thesis

This thesis is divided into seven chapters. An introduction to the overall thesis and its contents are presented in this chapter one.

Chapter two reviews the background studies and related literature that help to understand the areas of concern. It started with review about the climate change happen in our mother earth. Then, it follows with the review on Malaysia's energy and residential stock trend and also review about the current residential building due to Malaysia climate. In this chapter two, explanation about fundamental concept of thermal comfort such as human physiology related to thermal balance, condition that provide thermal comfort zone and method for determining acceptable thermal condition in occupied spaces are also discussed in details. It outlines briefly the relationship between design of the building and building envelope system that suits with Malaysian climate for occupants comfort. Next are the review about theoretical basis of heat transfer of opaque building envelope and the general review about earth brick as wall material. This chapter concludes with discussion on some of the research methods and experimental procedures for earth brick studies utilised by previous researchers.

Chapter three outlines the methodology used for this thesis in general. For this study about thermal performance of residential house using interlocking compressed earth brick (ICEB), combination of three methods were used. It includes laboratory testing to obtain the thermal conductivity value of ICEB, field measurement and monitoring to prove thermal problems inside a terrace house as well as to obtain measurement data for validation of ECOTECT program, and simulation of computer modelling to investigate the thermal performance of ICEB when employed as wall material for building.

Chapter four presents the details explanation about the ICEB thermal properties testing using guarded hot plate. The data recorded during the laboratory testing were discussed in this chapter together with explanation about the equipment used and the experimental procedures.

Chapter five was about field study by conducting field measurement and monitoring in an existing intermediate terrace house in Batu Pahat, Johor. It was discussed in details about the selected sample house, equipments used and the procedure of conducting the field study. At the end of this chapter, result was discussed in details.

Chapter six discusses the ECOTECT simulation program to model the measured conditions of the existing intermediate terrace house in Batu Pahat. It describes in details about the input data and modelling procedures to correctly model the existing house. A comparison between measured and simulated operative temperatures using ECOTECT software is discussed to evaluate the accuracy of the ECOTECT program in simulating the indoor thermal performance. It also discussed the predicted result from parametric study using ECOTECT program in performing indoor temperature of intermediate terrace house when using ICEB as wall material.

The last chapter in this thesis, chapter seven presents the overall summary of the research, limitations and outlines some suggestions and recommendations for future research on thermal performance of ICEB.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The world is entering a new era addressing the challenge of climate change. Global warming is essentially the release of gasses into the atmosphere that are slowly raising the Earth's temperature. Shift of temperature will result in the hastened melting of the Earth's glaciers and ice peaks leading to a rise in the sea level and the erosion of shores. Global warming is caused by built up of greenhouse gases like carbon dioxide, water vapour, methane, chlorofluorocarbons (CFCs), nitrous oxide and ozone which trap energy on the Earth's surface (Mackle, C., 2001). The environmental crisis concerns a wide range of matters. The major themes into which concern are categorized are social and economic dimensions and conservation and management of the natural environment.

Social and economic dimensions concern issues such as poverty, consumption patterns, human population and health. Conservation and management issues cover atmospheric protection, land sources, ecosystem protection and waste management amongst other things. The three main environmental problems currently facing the planet are climate change, loss of biological diversity and population growth (Mackle, C., 2001). Of all global environmental problems, climate change is the most threatening to human being and in many respects the most intractable (Schipper and Meyers, 1994, p. 21).

Through Expert Rating Green Living Course Certification (2011), "some scientific concepts, the sun provide energy to the earth. 30% of the energy is reflected back out from Earth and the remaining 70% is absorbed by the Earth, warming the lands, oceans and atmosphere. That 30% reflected back out and is trapped in". The phenomena called "greenhouse gasses". Most gasses emitted into the atmosphere via clear cutting of lands and burning of fossil fuels to provide energy for domestic uses, construction, transportation and also industry. The greenhouse gasses that occur naturally are actually beneficial if balance in nature but since human add more gasses into the atmosphere; the gases are also trapped and add more heat to the natural heat put off by the greenhouse gases.

The major sources of greenhouse gas emissions come from energy production and consumption, industrial developments, land and marine resource use and development. Energy related CO_2 emissions account for 78% of global anthropogenic emissions and 64% of the world's greenhouse gas emission must be transformed (Schipper and Meyers, 1994). Whether it is re-orientating power generation mix away from fossil fuels and towards nuclear and renewable or maximising the efficiency of vehicles, appliances, homes and industries, or developing revolutionary technologies for future, almost all potential sources of lower emissions will need to be highlighted.

2.2 Energy Consumption in Malaysia's Residential Sector

Fossil fuels are largely consumed towards the production of electricity, which is then utilised for many purposes including regulating the climate inside buildings. Figure 2.1 shows 24.52% of a household's energy consumption is used for refrigerator, cooking, washing machine, heating, cooling, entertainment, lighting, and gas for kitchen (Centre for Environment, Technology & Development Malaysia, 2006).

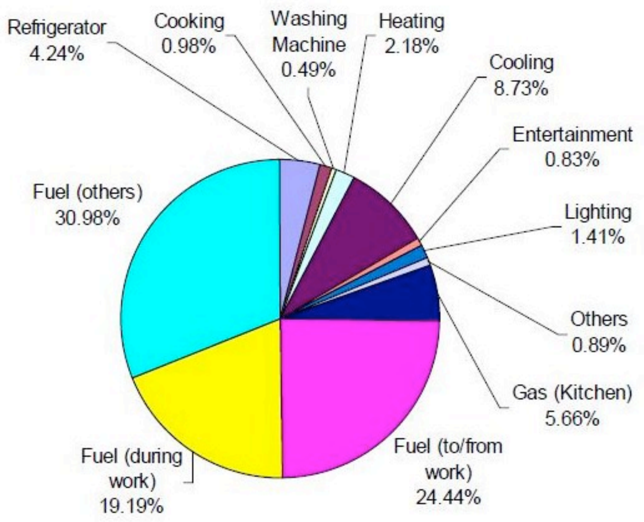

Figure 2.1: Average Household Energy Consumption (Centre for Environment, Technology & Development Malaysia, 2006)

While for home electricity consumption, the greatest energy demands in buildings come from satisfying our cooling needs. The chart in Figure 2.2 depicts that air conditioning takes up about 45% of the average household electricity consumption and air conditioning is the largest consumer of electricity in the house.

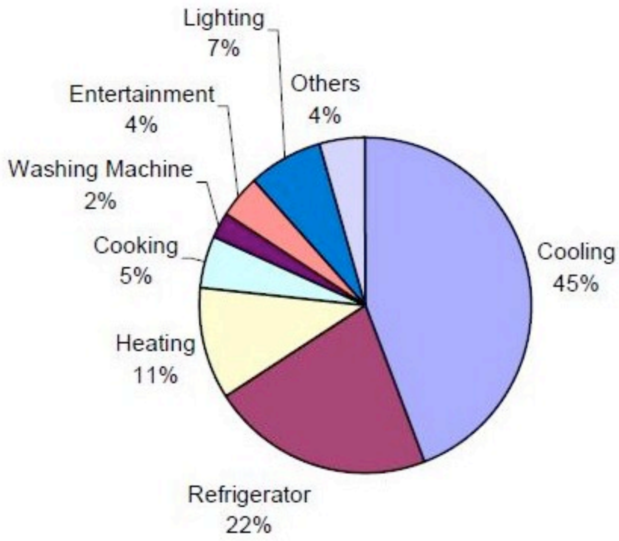

Figure 2.2: Average Home Electricity Consumption (Centre for Environment, Technology & Development Malaysia, 2006)

In residential sector, electricity demand is driven by growing number of households and the development in household income distribution. The electricity consumption per household depends on family size, living habits, number and age of electrical appliances and their hour of use (Mohd Taha, F., 2003). Wise use of electricity, as well as the use of efficient appliances will reduce energy, hence the electricity bills. The various appliances daily costs in terms of energy usage are given in Figure 2.3 below.

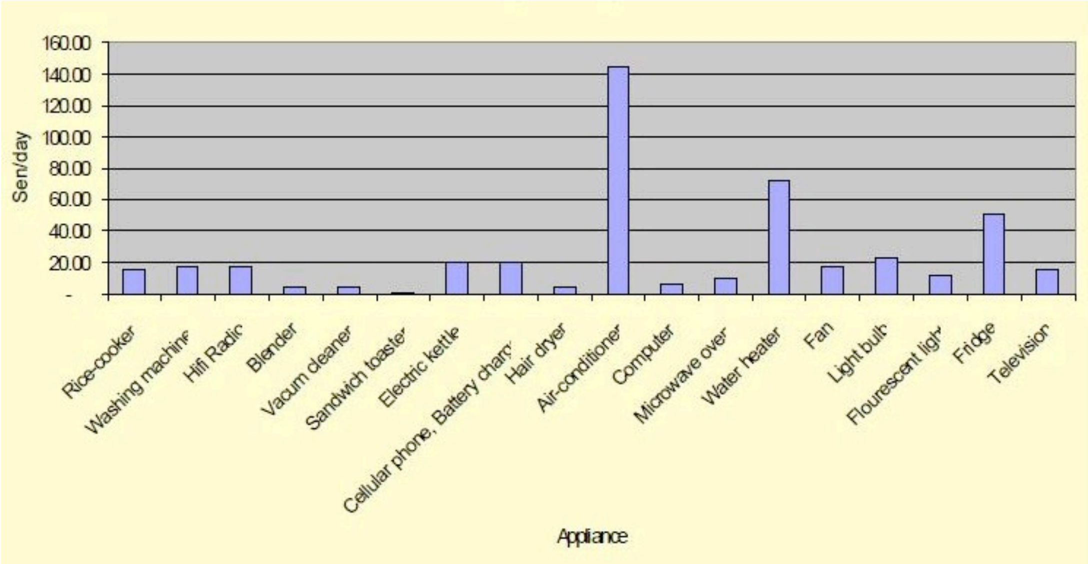

Figure 2.3: Appliances Daily Costs (Mohd Taha, F., 2003)

2.3 Current residential building design due to Malaysia Climate

One of the popular residential building types in Malaysia is a terraced house. Terrace houses are attached houses with similar facade treatment. Terrace houses are the form of housing in Malaysia in single or double storey. Each house unit occupies a rectangular lot with a land area between 130 and 170 square meters. The choicest unit, located on a corner lot is usually twice as large as the intermediate lots (Sadafi, *et al*., 2007). With such typical construction, the planning of these houses is usually predictable with deep living spaces, a smaller rear kitchen and bedrooms with toilet. Nevertheless, this typology remains the mainstay of the country’s mass housing strategy (Salleh, 1989).

However, developers have not put much effort into this sector. Several studies in Malaysia have revealed that the modern terrace houses have not been built accordance to the country’s climatic features (Takahashi, 1981). Many of the houses have been built in unsuitable orientations without appropriate shading design.

Because of Malaysia receives about 6 hours of sunshine per day with most places recording solar radiation ranging from 14 to 16 MJm^{-2} per day, building materials tend to collect heat most of the time (Sadafi, *et al*., 2007). Furthermore, house design has limited front and back openings on the building. It becomes worse if the house is intermediate lot. Obviously left and right sides of the building wall have no inlet and outlet for ventilation. But if all windows were opened (25% from the total floor area) the house could be more comfortable at night but still less comfortable during the day (Veronica, *et al.,* 1998). Due to these characteristics, we can claim that most terrace house designs have ignored the importance of thermal comfort zone in the interiors. Therefore, an investigation on climatic design considerations for fulfilment of thermal comfort in existing modern terrace houses seems necessary.

2.4 General Overview of Malaysian Climate

Climate is one of the most critical ways in which people experience place and it is no coincidence that an appropriate response to climate has forms an expressive feature of almost every great building tradition.

Malaysia which consists of Peninsular and East Malaysia lies between latitudes 1 and 7 degrees North, and longitude 100 and 119 degrees East. Climatic regions in Continental South-East Asia was classifies into Equatorial and Tropical. Peninsular Malaysia falls under the Equatorial type with the three main features of Malaysian climate are the seasonal uniformity, low wind velocity and the diurnal cycle (Takahashi, 1981). The main characteristics of Malaysian Climate are (Abd Halid A., 2007):

Air Temperature: Air temperature mostly uniform throughout the year. The average 24 hours mean value is only 27.7^{o}C whilst the average mean daily maximum exceeds 35^{o}C. However, the average mean daily minimum does not below 23^{o}C.

Humidity: High throughout the year, with average humidity above 79.2% and usually occur in the morning and 50% to 60% in the afternoon.

Rainfall: General pattern of rainfall in the Peninsular is related to the wind seasons. Change of the direction and speed of the airstreams are depends on seasons. Average yearly rainfall is about 2753.8 mm. The highest recorded amount of rainfall is in the East Coast region with an average annual rainfall of 505 mm in month of December. The least amount of rainfall is in month of January, February and March with an annual average of between 20-150 mm.

Sunshine: High humidity and cloud cover reduce direct solar radiation but increase in the proportion of diffuse radiation. The duration of daylight varies only slightly within 12 hours with direct solar radiation is more frequent in the afternoon (mean – 6 hours/day). The average daily range for the whole country is only 464 W/m^2.

Wind: Average wind speeds are low, annual mean – 1.0 m/s, with one or two predominant wind direction are usual. Wind directions vary at different times of the day. The distributions and characteristics of wind are determined by several global and local factors such as seasonal distribution of air pressure, the rotation of earth, the daily variation in heating and cooling of land and sea, the topography and surroundings of the region.

Sky: Fairy cloudy throughout the year, with 50% cloud cover or more. Thin in the early part of the day, and broken cloud at the middle, while thick cloud in the afternoon brings rain (usually convection).

The solar radiation received on the ground in most parts of the peninsular is mainly the diffuse radiation component rather than direct radiation. This situation is caused by the continuous presence of clouds in the atmosphere that reflect and scatter the solar radiation. Therefore, the radiation that reaches the ground is normally much diffused, which causes the uncomfortable sky glare. The continuous presence of cloud and water vapour in the atmosphere over peninsular Malaysia also reduces outgoing radiation at night. An overall view of the climatic condition in Malaysia indicates that the main environmental factors that affect thermal comfort in this region are solar radiation, high temperature and high humidity. Maintaining the body's heat balance will require extra effort due to these climatic stresses. Obviously, the primary source of heat gain to the body is direct radiation from the sun. As Malaysia receives direct solar radiation is more frequent in the afternoon (mean – 6 hours/day). With the average daily range for the whole country is about 464 W/m^2 per day, building materials tend to collect heat most of the time (Abdullah A. H., 2007). For building occupants, heat gain is contributed by conduction and radiation from the building fabric, hot air, as well as indirect solar radiation through windows and openings. Thermal comfort requirement in hot and humid conditions of Malaysia calls for the minimization of heat gain by the building fabric through solar radiation as well as heat gain by the human body while maximizing heat dissipation from the body by ventilation and evaporative cooling.

2.5 Thermal Comfort Requirements

Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE 1992, ISO 1984). Thermal comfort is a basic requirement for occupants to perform their day to day activities. The basic needs for human comfort are visual comfort by rendering natural and artificial illumination, acoustic environment by quiet services equipment and thermal comfort by consideration of thermal control systems (Chadderton, 1991). In several previous research investigations (Fanger, 1970; McIntyre, 1980; Gagge et al., 1986) thermal comfort is strongly related to thermal balance between the body's heat generations and the release of body heat into its surroundings. The body temperature must remain balanced and constant at around 37°C. In order to maintain this steady level, there are many physiological mechanisms of the body which can occur (McMullan, 1992).

2.5.1 Human Physiology Related to Thermal Balance

Physiological factors are primary importance with regard to comfort. The internal temperature of the human body must always keep within around 37°C. Any fluctuation from this value is a sign of illness and a rise of 5°C or drop of 2°C from this value can lead to death. This thermal balance is determined, on the one hand by the internal heat load and on the other, by the energy flow or thermal exchange between the body and the environment. As illustrated in Figure 2.4, there are four main modes of heat transfers between the human body and its environment which include radiation, conduction, evaporation and convection:

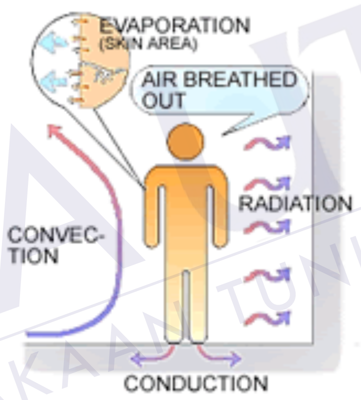

Figure 2.4: Ways of thermal exchange by the human body (Paul Gut & Dieter Ackerknecht, 1993)

1. Radiation

- Takes place between the human body and the surrounding surfaces such as walls and windows and in the open air, radiation takes place between the sky and sun. In this process temperature, humidity and air movement have practically no influence on the amount of heat transmitted. This amount of heat depends mainly on the difference in temperature between the person's skin and the surrounding or enclosing surface.

- The body may gain or lose heat by depending on whether the environment is colder or warmer than the body surface. When the surrounding temperature (air or surfaces) is above 25^{o}C, the clothed human body cannot get rid of enough heat by conduction, convection or radiation. It is recommended that the heat exchange by radiation is about 40% for a thermally comfortable state (Koenigsberger et al., 1973; Egan 1975; Chadderton, 1991).

2. Conduction

- Heat exchange process depends on the thermal conductivity of the materials in immediate contact with the skin. Conduction usually accounts for only a small part of the whole heat exchange. It is limited to local cooling of particular parts of the body when they come into contact with materials which are good conductors (direct contact i.e. clothing). Usually, there is very little heat transfer by conduction and it also depends on thermal insulation value of the cloth the body wearing. Besides, this is particular importance in the choice of flooring materials, especially where people usually sit on the floor.

3. Evaporation

- Heat loss takes place on the skin as insensible perspiration and sweat, while in the lungs through respiration and exhalation. During evaporation water absorbs heat; humans normally lose about one litre of water a day in respiration. The rate of evaporation depends on the amount of moisture transfer and on the air humidity. The lower the vapour pressure (dry air), and the greater air movement, the greater is the evaporation potential. Other variables such as temperature, speed of air, clothing and activity also affect the evaporation. Heat transfer by evaporation is about 20% (Koenigsberger et al., 1973; Egan 1975; Chadderton, 1991).

- The internal heat load of a body depends on its metabolic activity (met-value):

$$1 \text{ met} = 58 \text{ W/m}^2$$

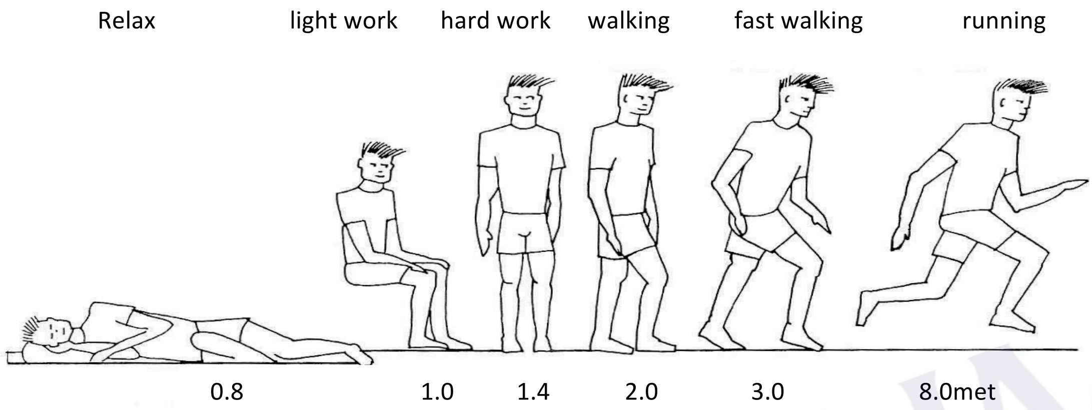

Figure 2.5: Metabolic rate of different activities (Fanger P. O., in: "Energy and Building" 3/1985)

4. Convection
   - Heat exchange by convection depends on two factors; difference temperature between the skin and the air and on air movement. It also controlled by adequate clothing. Body heat loss is primarily by convection is 40% (Koenigsberger et al., 1973; Egan 1975; Chadderton, 1991).

- The insulation effect of clothing can be expressed by a clothing value (clo-value):

$$1 \text{ clo} = 0.155 \text{ m}^2\text{K/W}$$

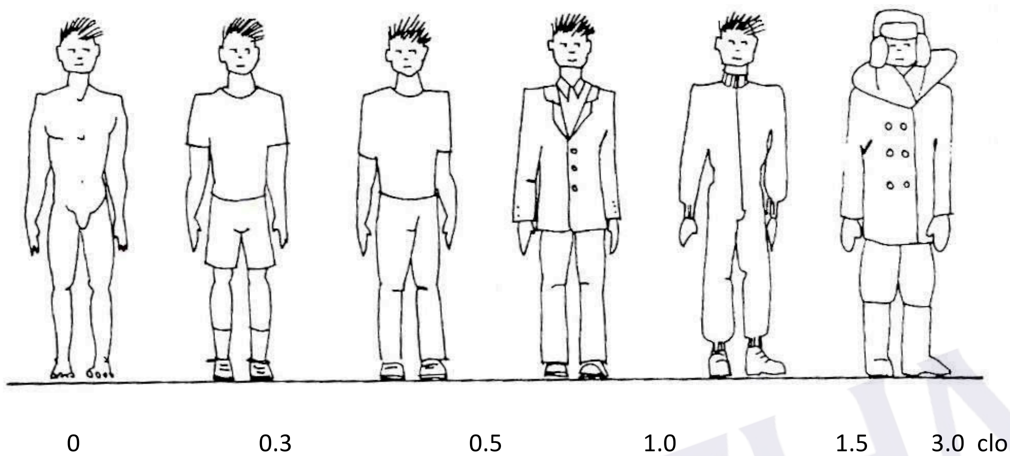

Figure 2.6: Insulation values of different kind of clothing (Fanger P. O., in: "Energy and Building" 3/1985)

There are six primary factors that must be addressed when defining conditions for thermal comfort. These factors are divided into two categories, these are individual and environmental factors. The individual factors are metabolic rate (M) and clothing insulation (I_{cl}) while the environmental factors are air temperature (T_a), relative humidity (rh), mean radiant temperature (T_{mrt}) and air velocity (v) (Fanger, 1970). In order to provide a thermally comfortable environment, proper combinations of the above variables have to be sought.

The body constantly produces heat from the consumption and digestion of food and the processes are known as metabolism of the energy produced in the body (Koenigsberger et al., 1973). About 80% must be dissipated to the environment while only 20% is utilized in useful work. The body's heat balance can be expressed as (Auliciems and Szokolay, 1997):

$$M \pm R \pm C_v \pm C_d - E = \Delta S \tag{2.1}$$

Where	M	: metabolic rate
	R	: net radiation
	C_v	: convection
	C_d	: conduction
	E	: evaporation heat loss
	ΔS	: change in the heat stored

If ΔS are zero, it is the state of thermal balance between the body and its environment. If positive, the body temperature increases, and if negative, the body temperature decreases (Auliciems and Szokolay, 1997).

Many laboratory and field studies have been conducted to define the thermal conditions that satisfy a wide range of occupants. Two widely used models developed in laboratories are the Fanger model and the Gagge two-node model (Jones, 2002). The models are based on heat balance equations of human body with the surrounding environment. Among the two, Fanger model "Comfort Equation" is the widely accepted model that combines the six thermal comfort variables. For any type of clothing and activity, the comfort equation can calculate the combinations of air temperature, relative humidity, mean radiant temperature and air velocity that creates the optimal thermal comfort condition (Fanger, 1970). Fanger has developed many thermal comfort charts by solving this equation using a computer program that can be easily used by engineers.

2.5.2 Condition That Provide Thermal Comfort Zone

The optimum thermal condition can be defined as the situation in which the least extra effort is required to maintain the human body's thermal balance. The greater the effort that is required, the less comfortable the climate is felt to be (Paul Gut & Dieter Ackerknecht, 1993). Usually, the maximum comfort condition cannot be achieved. However, designer will build a house that provides indoor climate close to an optimum within certain range thermal comfort still experienced. This range is called the comfort zone. It differs with individuals. It also depends on the clothing worn, physical activity, and age and health condition. Although ethnic differences are not importance, the geographical location plays important role because of the habit and of the acclimatization capacity of individuals.

In order to evaluate the indoor thermal environment at a wider scale, Fanger has introduced the concept of Predicted Mean Vote "PMV" and Predicted Percentage of Dissatisfied "PPD" to predict the actual thermal sensation (Fanger, 1970). PMV is an index that gives on the ASHRAE seven-point thermal sensation scale:

Table 2.1: The ASHRAE scale of thermal sensation

ASHRAE Scale	Numbering of votes
Hot	3
Warm	2
Slightly warm	1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

+1, 0, -1 are considered to constitute the comfort zone. The PMV model uses heat balance principles to relate the six key factors of thermal comfort to the average response of people on the above scale (Figure 2.7). The PPD index is related to the PMV. It is based on the assumption that people voting +2, +3, -2, or -3 on the thermal sensation scale are dissatisfied, and the simplification that PPD is symmetric around a neutral PMV (ASHRAE-55, 2004).

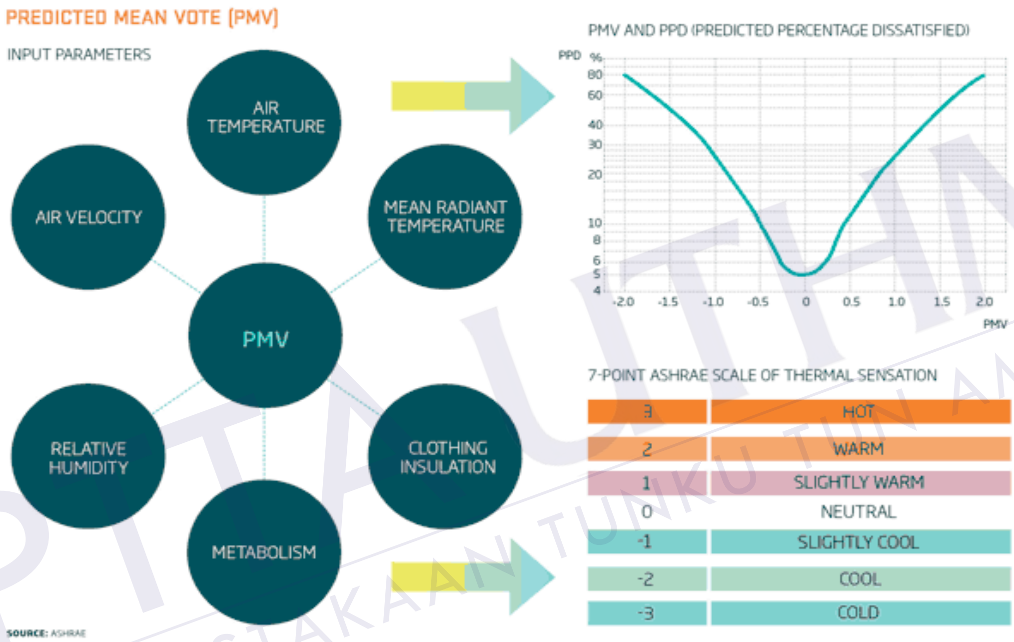

Figure 2.7: PPD as a function of PMV (ASHRAE-55, 2004)

Fanger model (PMV-PPD) is adopted in international thermal comfort standards: ISO-7730 (ISO, 1994), ASHRAE-55 (ASHRAE 55, 1992), and CR 1752 (CR 1752, 1998) to predict thermal comfort under steady state condition. ISO-7730-94 and ASHRAE-55-92 specify the acceptable thermal comfort condition based on a 10% PPD dissatisfaction criteria for general thermal comfort (Class B) and 10% dissatisfaction due to local discomfort which makes the level of thermal acceptability at 80%. On the other hand, CR 1752 is more flexible and recommends levels of acceptance for three classes of environment:

Class A: (-0.2 < PMV < +0.2, PPD < 6%)
Class B: (-0.5 < PMV < +0.5, PPD < 10%)
Class C: (-0.7 < PMV < +0.7, PPD < 15%)

However, the new ASHRAE standard (ASHRAE-55, 2004) includes all three classes as inclusion while it is expected that wider PMV range (Class C) will be included in ISO-7730 revision (Olesen & Parsons, 2002).

The old ASHRAE thermal comfort standard (ASHRAE-55, 1992) gives an ideal indoor thermal environment for two seasons: winter and summer at a specific combination of thermal comfort variables at 50% relative humidity: light activity level, typical summer and winter clothing habits, equal air and mean radiant temperature, and low relative air velocity. The shortcomings of the provided ideal thermal environment and new research findings in the field of thermal comfort under different climates have necessitated ASHRAE to update their old thermal comfort standards such as ASHRAE-55-92 and its amendment 55-95a.

ASHRAE has recently released the new thermal comfort standard ASHRAE-55 2004 (Olesen and Brager, 2004). Since both ISO-7730 standard and ASHRAE-55 2004 uses the same approach for thermal comfort zone determination, ASHRAE-55 2004 is chosen to represent the international thermal comfort standard in this research. The major departure from the old standards is the addition of the PMV-PPD method of determining the comfort zone without specifying the minimum level for humidity. It also introduces a new optional method for determining acceptable thermal conditions in naturally ventilated buildings.

2.5.3 Method for Determining Acceptable Thermal Condition in Occupied Spaces

A range of operative temperatures or a simple average of the air temperature and mean radiant temperature defines the comfort zone that provides acceptable comfort thermal environmental conditions. It is determined by specifying the values of humidity, air speed, metabolic rate and clothing insulation. The relation of these four factors is well illustrated in the bioclimatic chart below (Figure 2.8):

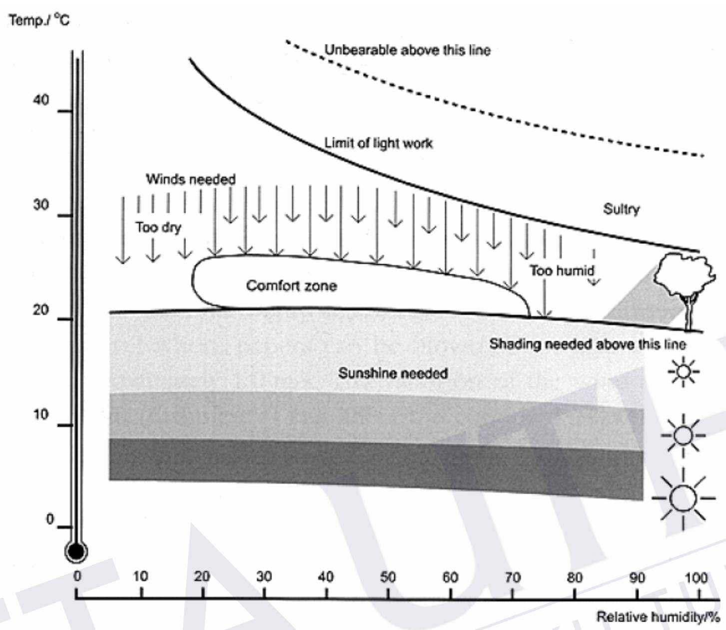

Figure 2.8: Bioclimatic chart (Olgyay Victor, 1963)

The chart indicates the zone where comfort is felt in moderate climate zones, wearing indoor clothing and doing light work. It also assumes that not only the air temperature but also the temperature of surrounding surfaces lie within this range.

The temperature limits might be either determined graphically for many typical applications or by using a computer program based on a heat balance model (PMV-PPD model) to determine the comfort zone for a wider range of applications.

2.5.3.1 Graphical Method for Typical Indoor Environments

This method can be applied to spaces where the occupants have activity levels that result in metabolic rates between 1.0 met and 1.3 met. The graphical method is also based on PMV-PPD model but assuming two different levels of clothing: 0.5 clo (typical for summer) and 1.0 clo (typical for winter), 10% PPD dissatisfaction criteria for general thermal comfort, and air speed less than 0.20 m/s. The range of operative temperatures is for 80% occupant acceptability. This is based on a 10% dissatisfaction criteria for general (whole body) thermal comfort based on the PMV-PPD index, plus with an additional 10% dissatisfaction that may occur on average from local (partial body) thermal discomfort. The operative temperature range allowed for intermediate values of clothing insulation may be determined by linear interpolation between the limits for 0.5 clo and 1.0 clo using the following relationships (Olesen B. W. & Brager G. S., 2004):

$$T_{min,\ Icl} = [(I_{cl} - 0.5\text{clo})\ T_{min,\ 1.0clo} + (1.0\text{clo} - I_{cl})\ T_{min,\ 0.5\text{clo}}] / 0.5\text{clo} \quad (2.2)$$

$$T_{max,\ Icl} = [(I_{cl} - 0.5\text{clo})\ T_{max,\ 1.0clo} + (1.0\text{clo} - I_{cl})\ T_{max,\ 0.5clo}] / 0.5\text{clo} \quad (2.3)$$

Where $T_{max,\ Icl}$: upper operative temperature limit for clothing insulation I_{cl},

$T_{min,\ Icl}$: lower operative temperature limit for clothing insulation I_{cl},

I_{cl} : thermal insulation of the clothing in equation (clo).

To increase the upper operative temperature limit for the comfort zone in certain circumstances, air speed greater than 0.20 m/s may be used.

2.5.3.2 Computer Model Method for General Indoor

For this method, it can apply to spaces where the occupants have activity level for metabolic rates between 1.0 met and 2.0 met and clothing 1.5 clo or less of thermal insulation. Computer program can also be used when the space conditions are different from those described in the graphical method. The specific values of humidity, air speed, clothing, and metabolic rate are main input data to the program. Consequently, the operative temperature range can be determined based on a PMV range of $-0.5 < PMV < +0.5$, which corresponds to a PPD of 10%.

2.5.3.3 Optional Method for Determining Acceptable Thermal Conditions in Naturally Conditioned Spaces

Many recent field studies have questioned the validity of PMV-PPD in predicting the thermal comfort conditions in naturally ventilated building (Olesen and Parsons, 2002). Field studies have found that thermal comfort can still be met at higher temperature ranges than those predicted by PMV-PD model. This discrepancy has led to a new concept of Adaptive Model (Humphreys and Nicol, 1998). Other studies have also shown that the adaptation could be achieved by many ways (Brager and deDear, 1998):

- Behavioural adjustments (personnel, environmental, technological or cultural)
- Physiological (genetic adaptation or acclimatization)
- Psychological (habituations or expectation)

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